LANSCE DIVISION TECHNOLOGY REVIEW

High-Energy Neutron Radiography as a Tool for Stockpile Surveillance

T.N. Taddeucci (LANSCE Division), A.B. Kaye (X Division), T.N. Claytor, C.L. Faust, T.O. Davis (ESA Division), and T.E. McDonald (P Division)

Introduction

High-energy neutron radiography has the potential to detect details in light materials contained within massive objects. However, practical applications in neutron radiography will require a suitably intense neutron source and an efficient detector system. We have been using the Target-4 spallation neutron source at the LANSCE Weapons Neutron Research (WNR) Facility to test neutron imaging and computed tomography (CT) techniques. Our measurements show that high-energy neutron radiography yields a level of contrast and resolution adequate to address specific stockpile surveillance needs.

The Challenge of High-Energy Neutron Radiography

A variety of radiographic techniques are available for applications in stockpile surveillance. The type of radiation best suited for a particular application (e.g., x-rays, gamma-rays, protons, and neutrons) depends on the resolution, count-rate, mass-sensitivity, and portability requirements of the problem at hand.

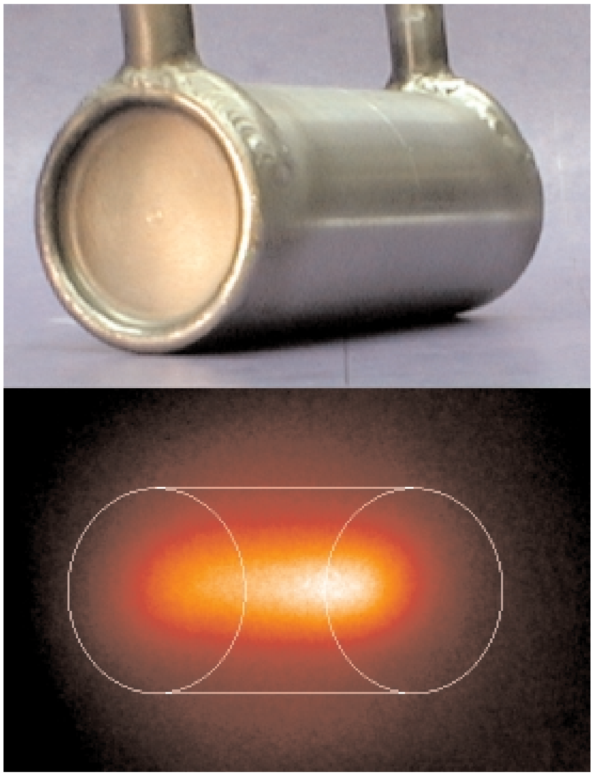
Matter is most transparent to neutrons having energies above several MeV. The neutron total cross section for all elements goes through a minimum for neutron energies near 300 MeV. Neutrons in this energy region can easily penetrate thick objects. Because neutrons interact via the strong interaction—that is, they scatter from the neutrons and protons in the atomic nucleus rather than the surrounding electron shells—sensitivity to light elements such as hydrogen is retained. This is in contrast to x-rays and gamma rays, which scatter primarily from electrons. High-energy neutrons may therefore be used in applications that require the inspection of hydrogenous layers shielded by heavier materials.

Reconstructing Radiographic Images in Three Dimensions

CT imaging reconstructs a three-dimensional image of an object (or equivalently, a set of two-dimensional cross-sectional slices) from a set of two-dimensional radiographic images. Several obstacles, however, must be overcome for CT imaging to become practical using high-energy neutrons. First, efficient neutron imaging detectors with good spatial resolution must be developed. The low cross section that makes matter relatively transparent to high-energy neutrons also makes high-energy neutrons hard to detect. Second, an intense source of high-energy neutrons is required. Sufficiently high detector efficiency and source intensity are required to obtain detailed CT images in a reasonable amount of time. Finally, an acceptable level of mass sensitivity (image contrast) and resolution must be demonstrated. The contrast and resolution in an image are affected by the physics of the scattering process in the object being studied and by the neutron detector, finite size and geometry of the neutron source, and background radiation (i.e., gamma rays and x-rays produced by the neutron source).

Initially, we demonstrated and measured the contrast and resolution of CT images using the WNR Target-4 spallation neutron source at LANSCE. This source produces a broad spectrum of neutrons ranging in energy from sub-MeV to several-hundred MeV and is therefore well suited for testing a variety of neutron-imaging techniques. With this neutron source, we accomplished the following:

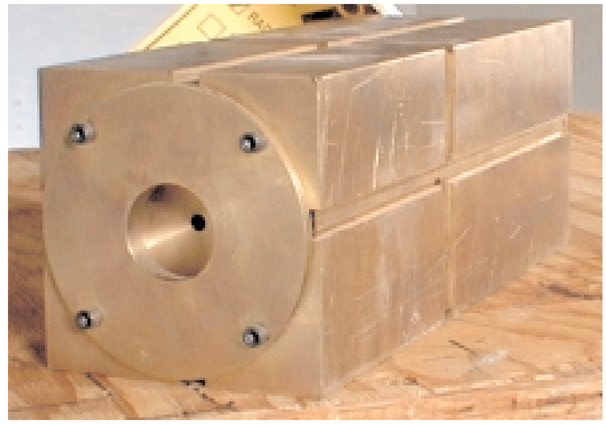
- tested two imaging systems—storage-phosphor image plates and amorphous silicon panels;
- detected holes in 20-mil Mylar sheets (75 mg/cm^2) and 31-mil plastic drafting templates (96 mg/cm^2) sandwiched between 3/4-in. iron plates; layers of aluminum, lead, and iron; and a 2-in.-thick uranium cube;
- performed neutron-activation measurements on a depleted-uranium (D_{38}) alloy cube and compared them to Monte Carlo estimates of activation products;
- used the intensity profile from the neutron shadow of the D_{38} cube to obtain a measurement of the combined source plus image-plate resolution;
- used a brass "pinhole" collimator to produce a neutron pinhole image of the WNR Target-4



▲ ***Fig. 1.*** *Replica of WNR Target-4 (top image). Target-4 is a 3-cm-diam, 7.5-cm-long tungsten cylinder surrounded by a water-cooling jacket. Neutron-pinhole image of Target-4 (bottom image). An outline of the inner tungsten cylinder is superimposed on the neutron image. In this image, the 800-MeV proton beam enters from the right.*

source, which allowed us to unfold the target contribution to the overall resolution and obtain the resolution of the detector (image plates) alone; and
- demonstrated CT imaging of a flat-plate object using storage phosphor image plates.

The pinhole image of WNR Target-4 (Fig. 1) provides a dramatic example of the difference between unmoderated high-energy neutron sources and moderated thermal cold-neutron sources that produce diffuse beams. The unmoderated Target-4 source yields neutrons that (for the most part) emerge in straight lines from their point of production. In this case, the laws of geometric optics apply and pinhole images can be formed in a manner directly analogous to light rays. For our measurement, we used a 27-cm-long brass collimator (Fig. 2) with a central aperture tapering to 1.6 mm at the center. This brass pinhole was located on the WNR 4FP30L flight path at a distance of 19 m from the target. The image was captured on storage-phosphor image plates located 40 m from the target.



▲ ***Fig. 2.*** *Brass collimator used to produce a neutron pinhole image of WNR Target-4. The collimator is 27 cm long with a central aperture that tapers to 1.6 mm in diameter at the center.*

Target-4 is a water-cooled, 3-cm-diam, 7.5-cm-long tungsten cylinder. At an aspect angle of 30°, this source has an apparent width of 3.75 cm. The following equation gives us the simple geometric estimate of the source contribution to image resolution.

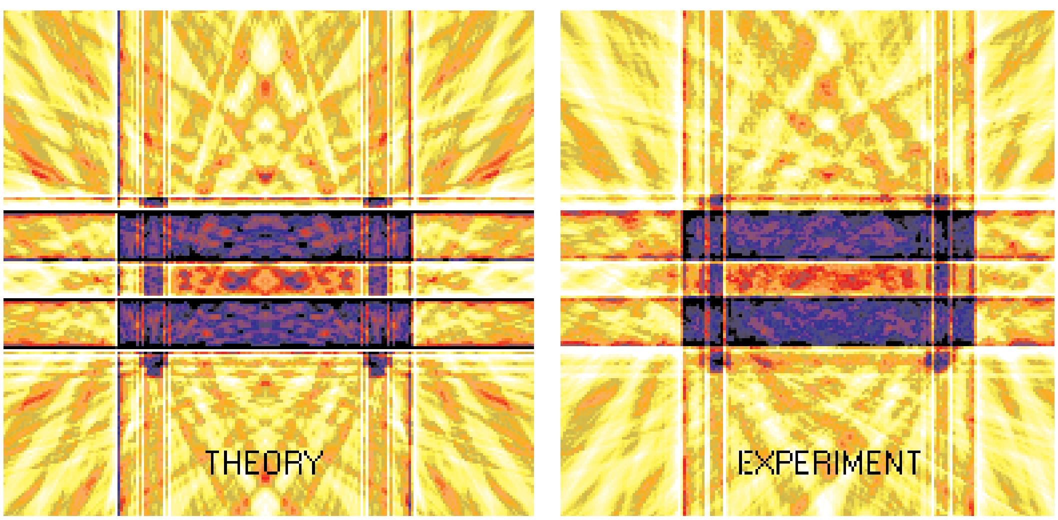
$$S1 = S0\ (L1/L0),$$

where

S1 = source contribution to image,
S0 = apparent source size,
L0 = source to object distance, and
L1 = object to detector distance.

An object-to-detector separation L1 of 0.5 m therefore yields a source contribution to the image resolution of slightly less than 0.5 mm for a source-to-object distance of 40 m. From our edge profile measurements with the D_{38} cube, we found that an eight-layer stack of image plates yielded a total line-spread function with a Lorentzian shape and a FWHM (full-width at half-maximum) of approximately 0.75 mm. The pinhole image will allow a detailed deconvolution of the Target-4 source contribution, but a simple estimate based on the above geometric arguments suggests that the neutron resolution of the image-plate stack is about 0.5 mm.

Because CT imaging is our ultimate goal, we used the image-plate detectors to produce a trial CT image of a flat-plate test object. The object consisted of two 3/4-in. steel plates separated by 1/2-in. aluminum spacers and held together with two 1/4-in. bolts. A 32-mil-thick plastic drafting template with a series of circular holes was sandwiched between the two plates. We obtained a sequence of twelve images and *(continued on page 4)*

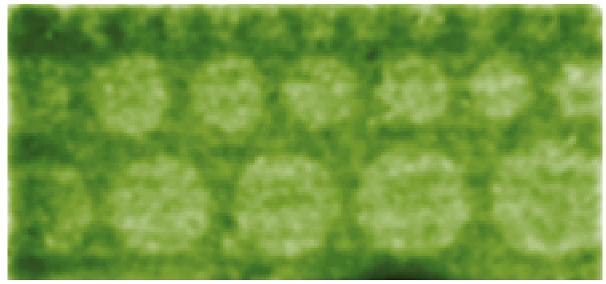


▲ ***Fig. 3.*** *Flat-plate assembly used for CT-imaging experiments (top image). CT reconstruction from twelve views of a horizontal cross section through the two bolts (bottom image).*

reconstructed the cross section through the horizontal plane containing the two bolts (Fig. 3). The agreement between the experimental image and a calculated model using known total neutron cross sections was very good.

Additional calculations with this model show that at least 144 views will be required to see with confidence the holes in the plastic layer in a CT cross section. A single radiographic image of the plastic template is shown in Fig. 4.

We are currently working on producing a detailed CT image of a classified object using a portable D-T neutron generator and exploring new options for intense portable neutron sources. Also, an important development goal will be the selection of an imaging system—either a CCD imaging system or an amorphous-silicon panel—to replace the labor-intensive storage-phosphor plates, which require manual processing after every exposure. Both of these imaging systems will be able to electronically read out the image data without disturbing the physical placement of the detector. This capability will be an important feature for rapid, high-volume imaging.



▲ ***Fig. 4.*** *Radiographic image of holes in a plastic drafting template shielded by iron.*

For more information, contact T.N. Taddeucci (LANSCE Division), (505) 665-3114, MS H855, taddeucci@lanl.gov.

Produced by the LANSCE-4 communications team: Barbara Maes, Sue Harper, Garth Tietjen, Sharon Mikkelson, and Grace Hollen.

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